

Numerical and Experimental Analysis of Diesel Spray Dynamics including the Effects of Fuel Viscosity

By

Chin Heung Bong

Master of Engineering (Aerospace), RMIT University

Bachelor of Engineering (Aerospace), RMIT University

Graduate Certificate in Commercialisation, University of Tasmania

A dissertation submitted in fulfilment of the requirements for the

Degree of Doctor of Philosophy in Engineering

at the

National Centre for Maritime Engineering and Hydrodynamics

Australian Maritime College

University of Tasmania

November 2010



Dedication

To my parents Bong Chee Kong and Tay Ah Tet,
my sisters San Mei Bong and Siew Mai Bong
and my love, Yun Chen.



**Figure of a numerical predicted diesel spray computed using Star-CD v3.26 and
plot generated using Matlab v7.5.**

Declaration of Originality

I certify that this thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information duly acknowledged in the thesis, and to the best of the my knowledge and belief contains no material previously published or written by another person except where due acknowledgment is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.



Chin Heung Bong

Date : 10 / 11 / 2010

Statement of Authority of Access

This thesis may be made available for loan. Copying of any part of this thesis is prohibited for two years from the date this statement was signed; after that time limited copying is permitted in accordance with the Copyright Act 1968.



Chin Heung Bong

Date : 10 / 11 / 2010

Note: This thesis contains a number of colour photographs and graphs. Reproducing it without colour may affect the quality of the photographs and hinder the identification of the data in the graphs.

Abstract

The maritime transport industry carries the majority of global trade. Large ships use diesel engines that are significantly larger than automotive diesel engines and consume low quality heavy fuel oil (HFO). This project aimed to better understand the dynamics of long duration, high fuel viscosity diesel sprays that are typical of a marine engine and to improve the accuracy of CFD models used for optimisation of engine design. The project utilised both numerical methods and experimental methods. The numerical software package called "Star-CD v3.26" was used for the numerical simulation part of the project. For the gas phase, the Large Eddy Simulation turbulence model was employed throughout. New sub-models were added to the Star-CD software to improve the simulation accuracy. Experiments were conducted using a custom-built High Pressure Spray Chamber (HPSC). The experimental results provided verification of the simulation results.

Literature reviews showed that limited research has been done on long duration HFO sprays. Most literature is focused on high speed diesel sprays with short injection durations using low viscosity fuel with light components. The low fuel viscosity has negligible effect on the droplet breakup process and numerical modelling requires only a single component fuel. Such studies can not be applied in HFO due to the high viscosity, complex molecular structure, presence of liquid phase soot, and variable fuel density. As a result, this project aimed to perform a thorough study of the fundamental dynamics of such sprays.

Throughout this project, the spray was studied at the gas density equivalent to combustion chamber density of approximately 35 kg/m^3 and at room temperature. This allowed the dynamics of the spray to be studied in the absence of combustion and evaporation. In the case of the HFO combustion spray, the presence of high molecular weight components and the formation of carbonaceous residue means that the spray remains as a multiphase flow throughout the combustion period.

The first phase of the project involved evaluating Lagrangian-Eulerian multiphase numerical models. In each evaluation, the models were isolated so that only the effects from the model of interest were shown in the results without unwanted influence of other models. The evaluation found that the inter-droplet collision model required corrections which resulted in the development of the mesh independent O'Rourke collision model (MIOC). The collision model studies showed that the nozzle exit region and the initial droplet cluster region contained the highest collision rate. This was because the droplet population was dense and the droplet

velocities were high in these regions. The Kelvin-Helmholtz/Rayleigh-Taylor (KH-RT) hybrid breakup model and Taylor Analogy Breakup (TAB) based dynamic droplet drag model were programmed into Star-CD v3.26.

The second phase of the project involved conducting experimental analysis of the spray. The experiment was broken into three parts, namely: spray penetration and cone angle, light sheet Particle Image Velocimetry (PIV) and dropsize shadowgraphy using a long-distance microscope. The macro spray structure (penetration experiments) and PIV experiments showed evidence that surface instabilities from the shearing of the jet against the surrounding gas, and the in-flow of air into the low pressure region of the spray jet, forms the overall spray structure. The experiment confirmed that increasing gas density results in a lower penetration rate and larger cone angle. The increase of fuel viscosity had a negligible effect on the spray penetration but increased the cone angle. PIV measurements were performed on the spray droplets because it was difficult to externally introduce seeding particles. As a result, it was not possible to adjust the seeding particle population density directly. The measured droplet velocities can be considered equivalent to the gas velocities in the sparse region of the spray because the numerical results suggested that there is minimal difference between the gas and droplet velocity. The spray images and the macro-PIV analysis showed the presence of high velocity regions and the presence of droplet clusters. The dropsize shadowgraphy experiments provided point velocity measurements that could be analysed using Particle Tracking Velocimetry (PTV) and μ -PIV methods. The results were compared with the macro-PIV results. The dropsize shadowgraphy results provided valuable dropsize data and confirmed that high fuel viscosity had a significant effect on the dropsize of the spray.

The third phase of the project involved the full numerical simulation of the diesel spray and validation with the HPSC experimental results. The validation confirmed that the KH-RT breakup model was able to reasonably predict the effects of fuel viscosity on dropsize, which was not the case with the Reitz-Diwakar breakup model. The penetration and cone angle validation showed very similar penetration rates in both numerical and experimental results, but the cone angle of the numerical simulation was narrower compared to the experimental results. The PIV measurements and simulation velocity profiles showed similar velocity patterns and velocity magnitudes at the sparse region of the spray. In the dense region, the velocity patterns remained similar but the magnitude of the predicted spray velocity was higher. This was because the experimental results were erroneous in the dense region, due to higher particle density leading to multiple scattering. The dropsize validation showed that the numerically predicted dropsize was slightly larger than the experimental results but consistent under all

conditions. It was concluded that the set-up using Large Eddy Simulation (LES) with Blob atomisation, KH-RT breakup model, MIOC model, TAB based droplet drag model and vertex based interpolation, produced the most accurate simulation when validated against the experimental results.

The full spray simulation suggested that the spray structure could be divided into two regions. The disintegration region showed that most of the breakup process and momentum transfer (from droplets to gas) occurred here. The stable region showed the formation of droplet clusters and volumetric expansion of the spray. The numerical simulation results showed that a high viscosity fuel spray contained significantly different internal structures compared to a low viscosity fuel spray. This was also partly supported by the experimental results. The high viscosity fuel spray droplet dispersion rate was significantly lower and the formation of droplet clusters occurred much further away from the nozzle, when compared to low viscosity fuel spray. The results also showed that an increase in gas density shortened the length between cluster formations.

The outcome of this project is improved understanding of long duration, high fuel viscosity diesel sprays. It is concluded that the use of LES as the turbulence model produces good qualitative internal spray structures that predict the instantaneous turbulent jet instability and the formation of droplet clustering. The project highlights the limitations in the current state of numerical prediction methods and recommendations are made for future work to improve numerical predictions.

Acknowledgement

First of all, I would like to thank my supervisors, Dr. Laurie Goldsworthy, and A. Prof. Paul Brander who have been a mentor and guide throughout my PhD. I am most grateful for the support from Dr. Laurie Goldsworthy who dedicated countless of hours of work and provided research fundings to complete my project. They have made this project very interesting and I have learnt countless of valuable lessons.

I would also like to give a special thank to Luciano Mason. He has been more than just a Guru to my fellow colleagues at the research centre and myself, but also been a great friend and a great role model.

I would also like to thank Prof. Neil Bose, Prof. Dev Ranmuthugala, Dr. Jonathan Binns and all the members of the department of National Centre for Maritime Engineering and Hydrodynamics at the Australian Maritime College for the funding and support of this project, without which the project would never have been possible.

I would like to thank my fellow students at the research centre who have given me much technical and more importantly, moral support. They are, in alphabetical order: Alan, Ben, Bryce, Indika, Nabeel, Roberto, Shinsuke, Saut, Susanne, Tim and last but not least, Dr. Vikram Garaniya.

I would like to thank my family for the great support and understanding. To my mom, my dad, my sisters and my love, Yun, I love you all very much.

Finally, I would like thank my friends, Mito, Andrea, Ugrin, Judy and Raja. I have been most fortunate to have known you all.

Table of Contents

ABSTRACT.....	I
ACKNOWLEDGEMENT.....	V
TABLE OF CONTENTS	VII
LIST OF FIGURES	XIII
LIST OF TABLES	XXIX
NOMENCLATURE.....	XXXIII
CHAPTER 1 INTRODUCTION.....	1
1.1 OBJECTIVES.....	1
1.2 METHODOLOGY	3
1.3 THESIS STRUCTURE	4
CHAPTER 2 LITERATURE REVIEW	7
2.1 PHYSICS OF A DIESEL SPRAY.....	7
2.1.1 <i>Macro Spray Structure</i>	8
2.1.2 <i>Micro Spray Structure and Small-Scale Physical Phenomena</i>	10
2.2 NUMERICAL MODELLING OF A DIESEL SPRAY	23
2.2.1 <i>Primary Atomisation Models</i>	27
2.2.2 <i>Secondary Breakup Models</i>	31
2.2.3 <i>Dynamic Droplet Drag Models</i>	38
2.2.4 <i>Inter-Droplet Collision Model</i>	39
2.2.5 <i>Multiphase Coupling</i>	43
2.2.6 <i>Gas-Phase Turbulence Models</i>	44
2.3 CONCLUDING REMARKS.....	45
CHAPTER 3 EVALUATION OF DIESEL SPRAY SIMULATION MODELS	47
3.1 ATOMISATION MODEL EVALUATIONS	49
3.1.1 <i>Set-up</i>	50
3.1.2 <i>Results</i>	52
3.1.3 <i>Concluding Remarks</i>	59
3.2 SECONDARY BREAKUP EVALUATIONS	60
3.2.1 <i>Star-CD Breakup Models Implementation</i>	61
3.2.2 <i>Model Set-up in Star-CD</i>	62
3.2.3 <i>Results</i>	65
3.2.4 <i>Concluding Remarks</i>	71

3.3	DYNAMIC DROPLET DRAG MODEL	72
3.3.1	<i>Validation of Drag Model Against Published Experimental Data</i>	72
3.3.2	<i>Results</i>	77
3.3.3	<i>Concluding Remarks</i>	80
3.4	INTER-DROPLET COLLISION	81
3.4.1	<i>Default O'Rourke Collision Model</i>	81
3.4.2	<i>Mesh Independent O'Rourke Collision (MIOC) Model</i>	83
3.4.3	<i>Collision Model Set-up</i>	86
3.4.4	<i>Results</i>	91
3.4.5	<i>Concluding Remarks</i>	106
3.5	RANS AND LES MODELLING TECHNIQUE COMPARISON	107
3.5.1	<i>Set-up</i>	108
3.5.2	<i>Results</i>	109
3.5.3	<i>Concluding Remarks</i>	114
3.6	MULTIPHASE COUPLING METHOD EVALUATION	115
3.6.1	<i>Set-up</i>	116
3.6.2	<i>Results</i>	118
3.6.3	<i>Concluding Remarks</i>	124
3.7	CONCLUSION	125
CHAPTER 4 EXPERIMENTAL STUDIES OF DIESEL SPRAY		129
4.1	EXPERIMENTAL SETUP DESCRIPTION	129
4.1.1	<i>Coordinate System of the HPSC</i>	130
4.2	SPRAY PENETRATION AND CONE ANGLE MEASUREMENT	132
4.2.1	<i>Experiment Set-Up</i>	132
4.2.2	<i>Experiment Results</i>	133
4.2.3	<i>Concluding Remarks</i>	145
4.3	SPRAY PARTICLE IMAGE VELOCIMETRY (PIV)	147
4.3.1	<i>Experiment Set-up</i>	147
4.3.2	<i>Results</i>	149
4.3.3	<i>Concluding Remarks</i>	156
4.4	DROPSIZE SHADOWGRAPHY	158
4.4.1	<i>Dropsizes Shadowgraphy Set-up</i>	158
4.4.2	<i>Results</i>	161
4.4.3	<i>Concluding Remarks</i>	176
4.5	CONCLUSION	177
CHAPTER 5 VALIDATION OF THE FULL SIMULATION		181
5.1	LIMITATIONS, ASSUMPTIONS AND BOUNDARY CONDITIONS	182

5.1.1	<i>In-Nozzle Simplification</i>	182
5.1.2	<i>Droplet Parcel Assumption</i>	183
5.1.3	<i>Mesh Size Limitation</i>	183
5.1.4	<i>Wall Assumption</i>	184
5.1.5	<i>Inter-Droplet Collision Assumption</i>	184
5.1.6	<i>Stripping Breakup Simplification</i>	185
5.2	SPRAY FULL SIMULATION SET-UP.....	187
5.2.1	<i>HPSC Interior</i>	188
5.2.2	<i>Mesh Design</i>	188
5.2.3	<i>Simulation Models</i>	191
5.2.4	<i>Simulation Conditions</i>	193
5.3	LAGRANGIAN MODEL EVALUATIONS.....	194
5.3.1	<i>Lagrangian Sub-Model Set-up</i>	195
5.3.2	<i>Atomisation Models Evaluation</i>	196
5.3.3	<i>Secondary Breakup Models Evaluation</i>	201
5.3.4	<i>MIOC Model Evaluation</i>	205
5.3.5	<i>Volumetric Dropsizes Distribution</i>	208
5.3.6	<i>Concluding Remarks</i>	213
5.4	DETAILED EXPERIMENTAL VALIDATION OF THE FINAL CFD CONFIGURATION.....	215
5.4.1	<i>Penetration and Cone Angle Validation</i>	216
5.4.2	<i>Dropsizes Validation</i>	225
5.4.3	<i>2D Vector Profile Validation</i>	228
5.4.4	<i>Concluding Remarks</i>	240
CHAPTER 6 DETAILED ANALYSIS OF THE SPRAY USING CFD		241
6.1	MACRO SPRAY STRUCTURE ANALYSIS	241
6.2	FUEL FRACTIONAL VOLUME STRUCTURE	249
6.2.1	<i>Cross-Section Plots and ISO Plots using Matlab v7.5</i>	250
6.2.2	<i>Detailed Fractional Volume Description</i>	251
6.2.3	<i>Fractional Volume Comparison at Different Chamber Pressures</i>	260
6.2.4	<i>Fractional Volume Comparison at Different Fuel Viscosities</i>	261
6.3	DROPSIZE PROFILE OF THE SPRAY.....	262
6.3.1	<i>Detailed Dropsizes Description</i>	262
6.3.2	<i>Dropsizes Comparison at Different Chamber Pressures</i>	266
6.3.3	<i>Dropsizes Comparison at Different Fuel Viscosities</i>	266
6.4	VELOCITY PROFILE OF THE SPRAY	267
6.4.1	<i>Detail Velocity Description</i>	268
6.5	CONCLUDING REMARKS.....	273

6.5.1	<i>The Disintegration Region and the Stable Region</i>	273
6.5.2	<i>Spray Core Properties</i>	274
6.5.3	<i>Droplet Cluster Properties</i>	274
CHAPTER 7 SUMMARY AND CONCLUSIONS		277
7.1	CONCLUSION OVERVIEW	282
7.2	RECOMMENDATIONS FOR FUTURE WORK.....	284
REFERENCES		287
BIBLIOGRAPHY		294
APPENDIX A - EXPERIMENTAL SETUP SPECIFICATION		299
A.1	AMC HIGH PRESSURE SPRAY CHAMBER (HPSC)	299
A.2	INJECTION SYSTEM	300
A.3	INSTRUMENTATION.....	302
APPENDIX B - EXPERIMENT DESCRIPTIONS		307
B.1	SPRAY PENETRATION AND CONE ANGLE SET-UP.....	310
B.1.1	<i>Camera Alignment and Scale Calibration</i>	310
B.1.2	<i>Camera and Laser Light Set-up</i>	310
B.1.3	<i>Limits of CCD Camera</i>	311
B.2	PIV EXPERIMENT SET-UP	312
B.3	DROPSIZE SHADOWGRAPHY SET-UP	317
B.3.1	<i>Equipment Set-up</i>	318
B.3.2	<i>Dropsizes Measurement Calibration</i>	319
APPENDIX C - NOZZLE FLOW RATE MEASUREMENT		323
C.1	NOZZLE FLOW RATE MEASUREMENT PROCEDURE.....	325
C.2	NOZZLE FLOW RATE RESULTS	325
C.3	AVERAGE MASS FLOW RATE.....	326
C.4	INSTANTANEOUS MASS FLOW RATE AND DISCHARGE COEFFICIENT.....	327
C.5	SIMULATION INJECTION PROFILE.....	329
C.6	CONCLUDING REMARKS	329
APPENDIX D – EXPERIMENTAL DATA ANALYSIS METHODOLOGY		331
D.1	SPRAY PENETRATION AND CONE ANGLE DATA ANALYSIS.....	331
D.1.1	<i>Spray Tip Penetration Definition and Calculation Method</i>	332
D.1.2	<i>Spray Cone Angle Definition and Calculation Method</i>	333
D.2	PIV DATA ANALYSIS.....	338
D.2.1	<i>Error Analysis</i>	338

D.3	DROPSIZE MEASUREMENT DATA ANALYSIS	344
D.3.1	<i>Image Preprocessing</i>	345
D.3.2	<i>Particle Recognition</i>	348
D.3.3	<i>Particle Segmentation and Recognition Filter</i>	348
D.3.4	<i>Statistical Calculations and Corrections</i>	349
D.3.5	<i>Particle Tracking Velocimetry</i>	350
D.3.6	<i>Micro PIV Analysis Technique</i>	352
D.4	ADDITIONAL DROPSIZE MEASUREMENT DATA ANALYSIS WITH MATLAB v7.5	354
D.4.1	<i>Percentage Error Calculation</i>	358
APPENDIX E - INSTANTANEOUS PIV RESULTS.....		361
APPENDIX F - CLUSTER-COMPUTING BENCHMARK		363

List of Figures

Figure 2-1 Tip penetration of a diesel spray and biodiesel spray with $P_i=80$ MPa injection pressure and gas pressure ranging from 20 to 40 bar. $D_{noz}=300\text{ }\mu\text{m}$; $L/D=2.67$; $t_3=1.2$ ms. (Courtesy of Park et al. [9]).....	9
Figure 2-2 Overall SMD of diesel spray and biodiesel spray at $P_i=60$ MPa injection pressure and $P_a=1$ bar gas pressure. $D_{noz}=300\text{ }\mu\text{m}$; $L/D=2.67$; $t_3=1.2$ ms. (Courtesy of Park et al. [9]) .	10
Figure 2-3 Two photographs showing a periodic in-nozzle cavitation. Flow from left to right. Upstream pressure=120 bar, downstream pressure=40 bar. (Courtesy of Schmidt et al. [15]).....	11
Figure 2-4 Photograph of a water jet showing the surface instability of the liquid core surface. (Courtesy of Lefebvre [6])	13
Figure 2-5 A shadowgraphy picture of droplet breakup process under exposure to high air velocity. The droplet breaks up under a catastrophic regime with both KH and RT instability present in the process. Diesel fuel, $We=383$ and $D_0=184\text{ }\mu\text{m}$. (Courtesy of Park et al. [23]).....	16
Figure 2-6 Four different outcomes from an inter-droplet collision. The outcomes are coalescence, reflexive separation, stretching separation and bounce. (Courtesy of Ko and Ryou [31])	18
Figure 2-7 Diagram illustrating the variables B , $D1$ and $D2$ of two impacting droplets used in equation (2.4). (Courtesy of Ko and Ryou [31])	19
Figure 2-8 Plot showing the four different collision outcomes with respect to impact parameter b and We when the two droplet diameters are the same ($\Delta=1$). (Courtesy of Ko and Ryou [31]).....	20
Figure 2-9 A photograph of a diesel spray showing regions of large eddies. Image is taken via LIF imaging. The eddies are highlighted from A to E. $D_{noz}=170\text{ }\mu\text{m}$, $L/D=5.588$, $P_i=50$ MPa, $P_a=20$ bar, $t_1=4$ ms, $t_3=2$ ms. (Courtesy of Cao et al. [39]).....	22
Figure 2-10 Turbulent energy and coupling level of droplet particle multiphase flow with gas fluid with respect to fractional volume ϕ . (Courtesy of Sirignano [30]).....	23
Figure 2-11 The liquid core profile of MPI-1 atomisation model [47]. The profile has an elliptical shape.....	28
Figure 2-12 The liquid core profile of MPI-2 atomisation model [47]. The profile shape is a cone.	29
Figure 2-13 An illustration of the Blob atomisation model. (Courtesy of Baumgarten [22]).....	31

Figure 2-14 An illustration of the particle distortion concept in the TAB model.	38
Figure 2-15 Top-down view of a diesel spray showing the clover-leaf effect found in a spray simulation with Cartesian meshing. (Courtesy of Hieber [67]).....	41
Figure 3-1 Diagram of the interactions between sub-models in the Lagrangian phase and the turbulence model in the Eulerian phase in a multiphase diesel spray simulation.....	48
Figure 3-2 SMD of Huh-Gosman atomisation at different injection pressures with respect to different ambient gas densities. $D_{noz}=240\text{ }\mu\text{m}$ and $C_d=0.76$. See Table 3-1 and Table 3-2 for details.	53
Figure 3-3 Half cone angle of the diesel spray from Huh-Gosman atomisation at different injection pressures and ambient gas densities. $D_{noz}=240\text{ }\mu\text{m}$ and $C_d=0.76$. See Table 3-1 and Table 3-2 for details.	54
Figure 3-4 SMD of MPI-1 atomisation at different injection pressures with respect to different ambient gas densities. $D_{noz}=240\text{ }\mu\text{m}$ and $C_d=0.76$. See Table 3-1 and Table 3-2 for details.	55
Figure 3-5 SMD of MPI-2 atomisation at different injection pressures with respect to different ambient gas densities. $D_{noz}=240\text{ }\mu\text{m}$ and $C_d=0.76$. See Table 3-1 and Table 3-2 for details.	56
Figure 3-6 Droplet volume CDF distribution with respect to the Weber number of three atomisation models. $D_{noz}=240\text{ }\mu\text{m}$, $C_d=0.76$, $P_i=100\text{ MPa}$ and $\rho_a=34.5\text{ kg/m}^3$. See Table 3-1 and Table 3-2 for details.....	58
Figure 3-7 Cavitation number chart with respect to Reynolds number. (Courtesy of Suh and Lee [76])	64
Figure 3-8 Penetration plot of the experiment at $P_i=60\text{ MPa}$ compared with KIVA-3 KH-RT breakup model ($B_1=40$, $C_3=0.3$), Star-CD KH-RT breakup model ($B_1=40$, $C_3=0.3$) and Star-CD Reitz-Diwakar breakup model.....	66
Figure 3-9 Penetration plot of the experiment at $P_i=80\text{ MPa}$ compared with KIVA-3 KH-RT breakup model ($B_1=40$, $C_3=0.3$), Star-CD KH-RT breakup model ($B_1=40$, $C_3=0.3$) and Star-CD Reitz-Diwakar breakup model.....	67
Figure 3-10 Penetration plot of the experiment at $P_i=60\text{ MPa}$ compared with Star-CD KH wave breakup model at different values of B_1 coefficient.	68
Figure 3-11 Global SMD plot of $P_i=60\text{ MPa}$ spray against time of different breakup models, namely KIVA-3 KH-RT model ($B_1=40$, $C_3=0.3$), Star-CD KH-RT model ($B_1=40$, $C_3=0.3$), Star-CD KH wave model ($B_1=1.7$) and Star-CD Reitz-Diwakar model.	69

Figure 3-12 Global SMD plot of $P_i=80$ MPa spray against time of different breakup models, namely KIVA-3 KH-RT model ($B_1=40$, $C_3=0.3$), Star-CD KH-RT model ($B_1=40$, $C_3=0.3$), Star-CD KH wave model ($B_1=1.7$), and Star-CD Reitz-Diwakar model.	70
Figure 3-13 Global SMD plot of $P_i=60$ MPa spray against time of Star-CD KH wave breakup models ($B_1=1.7$, 7.5, 10 and 40).	71
Figure 3-14 A schematic of the experiment by Park et al. [23] showing the droplet generator and gas nozzle. The piezo droplet generator injects a mono-sized droplet of $D_0=184 \mu\text{m}$ at 97.2 mg/s.	73
Figure 3-15 Schematic of the PDPA system used by Park et al. [23]. This system was used for measuring dropsize and velocity.	73
Figure 3-16 Set-up of the shadowgraphy observation system by Park et al. [23]. This system was used for droplet visualisation and the study of droplet deformation.	73
Figure 3-17 Diagram of the arbitrary volume outline used for Star-CD numerical simulation to simulate the Park et al. [23] droplet breakup experiment. The dimensions of this arbitrary volume was 30 x 30 x 40 mm.	74
Figure 3-18 Cross-section of the mesh set-up for the single droplet simulation with fine mesh located at the gas nozzle exit and coarse mesh occupying the rest of the volume. The mesh length of the fine mesh and coarse mesh were 0.333 mm (average measurement) and 1.25 mm respectively.	75
Figure 3-19 Top down view of the mesh volume showing the adapted circular shape for the gas nozzle exit. The circular mesh replicated the round gas nozzle found in the experiments Park et al. [23].	75
Figure 3-20 Comparison of droplet path of Park et al's experiment, default drag model and dynamic drag model at $We=4.3$. Fuel=diesel, $D_0=184 \mu\text{m}$, $u_0=13.4 \text{ m/s}$, $\rho_a=1.15 \text{ kg/m}^3$ and $u_{inj}=22.5 \text{ m/s}$ (see Table 3-5 and Table 3-6).	77
Figure 3-21 Comparison of droplet path of Park et al's experiment, default drag model and dynamic drag model at $We=13$. Fuel=diesel, $D_0=184 \mu\text{m}$, $u_0=13.4 \text{ m/s}$, $\rho_a=1.15 \text{ kg/m}^3$ and $u_{inj}=28.73 \text{ m/s}$ (see Table 3-5 and Table 3-6).	79
Figure 3-22 Comparison of droplet path of Park et al's experiment, default drag model and dynamic drag model at $We=26.6$. Fuel=diesel, $D_0=184 \mu\text{m}$, $u_0=13.4 \text{ m/s}$, $\rho_a=1.15 \text{ kg/m}^3$ and $u_{inj}=55.4 \text{ m/s}$ (see Table 3-5 and Table 3-6).	79
Figure 3-23 Predicted drag coefficient (C_D) plot with respect to x-axis of the three cases. $we=4.3$, $we=13$, $we=26.6$. Fuel=diesel, $D_0=184 \mu\text{m}$, $u_0=13.4 \text{ m/s}$ and $\rho_a=1.15 \text{ kg/m}^3$	80

Figure 3-24 Three mesh volumes with length 0.67 mm (a), 1.0 mm (b), and 1.5 mm (c). Droplets were injected from the nozzle at the top of the cell. Rosin-Rammler distribution with $X=6.2e-5$, $q=1.7$ was used. $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, standard collision model. See Table 3-9 and Table 3-10.....	82
Figure 3-25 A small region of volume occupied by droplets in a latter part of the spray where droplets have scattered over many cell volumes. $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, $t_i=8\text{ ms}$, standard collision model and mesh size 1 mm. See Table 3-9 and Table 3-10.....	83
Figure 3-26 Illustration of two colliding parcels and the arbitrary volume which the two parcels occupy. This is the analogy used for the Mesh Independent O'Rourke collision model....	84
Figure 3-27 Tip penetration plot of the no collision spray with respect to time and different cell sizes: 0.67 mm; 1.0 mm and 1.5 mm. Setting 1 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).....	91
Figure 3-28 Total SMD plot of the no collision spray with respect to time and different cell sizes: 0.67 mm; 1.0 mm and 1.5 mm. Setting 1 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).....	92
Figure 3-29 Total SMD plot of the standard collision spray with respect to time and different mesh sizes: 0.67 mm; 1.0 mm and 1.5 mm. Setting 2 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10)..	93
Figure 3-30 Coalescence frequency of the standard collision model with respect to time. Setting 2 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).	94
Figure 3-31 Total SMD plot of the standard collision model + Nordin's Constraint + Neighbouring Cell Search with respect to time. Cell sizes: 0.67 mm; 1.0 mm and 1.5 mm. Setting 3 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).....	95
Figure 3-32 Coalescence frequency of the standard collision model + Nordin's Constraint + Neighbouring Cell Search with respect to time. (see Setting 3 in Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, (See Table 3-9 and Table 3-10).	96
Figure 3-33 Total SMD plot of the standard collision spray + Nordin's Constraint + Coalescence Timescale + Neighbouring Cell Search with respect to time. Cell size: 0.67 mm; 1.0 mm and 1.5 mm. Setting 4 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).....	97

Figure 3-34 Coalescence frequency of the standard collision model + Nordin's Constraint + Coalescence Timescale + Neighbouring Cell Search with respect to time (see setting 4 in Table 3-11). $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, (See Table 3-9 and Table 3-10).	98
Figure 3-35 Total SMD plot of the MIOC spray with respect to time. Cell size: 0.67 mm; 1.0 mm and 1.5 mm. Setting 5 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).	100
Figure 3-36 Coalescence frequency of the MIOC model with respect to time. Setting 5 (see Table 3-11), $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).	101
Figure 3-37 Comparison of the different collision settings at mesh size 0.67 mm. Details of the settings found in Table 3-11. $D_{noz}=240\text{ }\mu\text{m}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$ (See Table 3-9 and Table 3-10).	102
Figure 3-38 Four figures showing a cross-section view of the spray of different settings. (a) no collision; (b) standard O'Rourke collision with Nordin's constraint and neighbouring cell level turned on; (c) standard collision with Nordin's constraint, coalescence timescale and neighbouring cell level turned on; (d) MIOC with Nordin's constraint, coalescence timescale and neighbouring cell level turned on. $D_{noz}=0.24\text{ mm}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, $t_i=8\text{ ms}$, cell size = 1 mm (See Table 3-9 and Table 3-10).	103
Figure 3-39 Three diagrams showing the cross-section spray with different collision settings and coalescence highlighted with a red star. (a) standard O'Rourke collision only; (b) standard O'Rourke collision + Nordin's constraint + neighbouring cell level; (c) MIOC + Nordin's constraint + coalescence timescale + neighbouring cell level. $t_i=8\text{ ms}$, $t_{i2}=0.2\text{ ms}$, $D_{noz}=0.24\text{ mm}$, $P_i=100\text{ MPa}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, mesh size=0.67 mm (See Table 3-9 and Table 3-10).	104
Figure 3-40 Cross-section SMD plot of the LES diesel spray simulation with different mesh lengths (0.67 mm, 1.0 mm, 1.5 mm). No collision, $P_i=100\text{ MPa}$, $D_{noz}=240\text{ }\mu\text{m}$, mass flow rate 0.014 kg/s , $\rho_a=34.5\text{ kg/m}^3$, $t_i=5\text{ ms}$ (See Table 3-9 and Table 3-10).	105
Figure 3-41 Droplet distribution plot of simulation using LES technique. $P_i=100\text{ MPa}$, $D_{noz}=240\text{ }\mu\text{m}$, $P_a=30\text{ bar}$, $t_i=5\text{ ms}$, cross-section thickness=0.4 mm.	109
Figure 3-42 Droplet distribution plot of simulation using RNG k- ϵ RANS technique. $P_i=100\text{ MPa}$, $D_{noz}=240\text{ }\mu\text{m}$, $P_a=30\text{ bar}$, $t_i=5\text{ ms}$, cross-section thickness=0.4 mm.	110

Figure 3-43 Velocity profile plot of simulation using LES technique. $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, cross-section thickness=5.0 mm.	111
Figure 3-44 Velocity profile plot of simulation using LES technique at equivalent magnification of PIV experiment (see section 4.3). $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, cross-section thickness=5.0 mm.	112
Figure 3-45 Velocity profile plot of simulation using RNG k- ϵ RANS technique. $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, cross-section thickness=5.0 mm.	113
Figure 3-46 Velocity profile plot of simulation using RNG k- ϵ RANS technique at equivalent magnification of PIV experiment (see section 4.3). $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, cross-section thickness=5.0 mm.	113
Figure 3-47 Coalescence plot of simulation using LES technique. $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=8$ ms, $t_{12}=0.2$ ms, cross-section thickness=1.0 mm.	114
Figure 3-48 Coalescence plot of simulation using RNG k- ϵ RANS technique. $P_i=100$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=8$ ms, $t_{12}=0.2$ ms, cross-section thickness=1.0 mm.	114
Figure 3-49 An illustration showing the top down view at the point of fuel injection and the corresponding vertex location and cell centre location.	116
Figure 3-50 Mesh set-up used for the coupling method evaluation. Top view (left), side view (middle) and cross-section view (right).	117
Figure 3-51 Top down view of droplet location with cell (left), gradient (middle), and vertex (right) interpolation with no collision. $P_i=110$ MPa, $D_{noz}=240$ μm , mass flow rate 0.014 kg/s, $\rho_a=34.5$ kg/m ³ , $t_1=0.25$ ms.	119
Figure 3-52 Top down view of droplet location with cell interpolation method and no collision highlighting the gaps at the horizontal and vertical axes.	119
Figure 3-53 Plot of the centre of mass with respect to polar coordinates from 0° to 90° (case 1, 2 and 3) with no collision.	121
Figure 3-54 Top down view of droplet location with cell (left), gradient (middle), and vertex (right) interpolation methods with standard collision model. $P_i=110$ MPa, $D_{noz}=240$ μm , mass flow rate 0.014 kg/s, $\rho_a=34.5$ kg/m ³ , $t_1=0.25$ ms.	121
Figure 3-55 Plot of the centre of mass with respect to polar coordinates from 0° to 90° (case 4, 5 and 6) with standard collision model.	123
Figure 3-56 Top down view of droplet location with cell (left), gradient (middle), and vertex (right) interpolation methods with MIOC model. $P_i=110$ MPa, $D_{noz}=240$ μm , mass flow rate 0.014 kg/s, $\rho_a=34.5$ kg/m ³ , $t_1=0.25$ ms.	123

Figure 3-57 Plot of the centre of mass with respect to polar coordinates from 0° to 90° (case 7, 8 and 9) with MIOC model.	124
Figure 4-1 Photograph of the HPSC showing the calibration set-up for dropsize shadowgraphy measurements.	130
Figure 4-2 ISO diagram of the assembled AMC HPSC chamber with details of the coordinate system. (Courtesy of Goldsworthy et al. [79])	131
Figure 4-3 overhead view of the equipment set-up with the layout of laser and camera for the PIV and shadowgraph measurements. (Courtesy of Goldsworthy et al. [79])	131
Figure 4-4 Penetration of spray with respect to time at 20, 30 and 40 bar chamber pressure. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	134
Figure 4-5 Measured penetration data with corresponding predicted penetration from Hiroyasu and Arai's empirical formula [5]. The chamber pressures were 20, 30 and 40 bar. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	135
Figure 4-6 Comparison of penetration with different viscosity fuels. The molecular viscosity of diesel, 50% canola oil and 75% canola oil were 0.0022 kg/(ms), 0.028 kg/(ms) and 0.042 kg/(ms) respectively. Avg. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	136
Figure 4-7 The normalised RMS of the spray tip penetration sample shown as a percentage. Each point represents the average of 10+ shots. Details of the experiments are found in Section B.1 and the fuel properties shown in Table 4-2. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_3=12$ ms.	137
Figure 4-8 Comparison of cone angle at different atmospheric pressures of 20, 30 and 40 bar. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	138
Figure 4-9 Comparison of cone spray angle with respect to spray tip penetration at different chamber pressures. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	139
Figure 4-10 Two diesel sprays at 4 ms (left) and 8 ms (right) after start of injection. Diesel fuel, avg. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μ m, $t_3=12$ ms.	140
Figure 4-11 Comparison of cone spray angle at different fuel viscosities with respect to time. The fuel properties are shown in Table 4-2. Avg. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μ m, $t_3=12$ ms. Each point represents the average of 10+ shots.	141

Figure 4-12 Comparison of cone spray angle plot with respect to spray tip penetration of different fuel viscosities. The fuel properties are shown in Table 4-2. Avg. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μm , $t_3=12$ ms. Each point represents the average of 10+ shots.....	142
Figure 4-13 The normalised RMS of the spray cone angle shown as a percentage. The results are taken from the five different experiments. Details of the experiments are found in Section B.1 and the fuel properties are shown in Table 4-2. Avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_3=12$ ms. Each point represents the average of 10+ shots.	143
Figure 4-14 Summary of the average cone angle of the spray with different experimental conditions. The red gas pressure bars are for diesel fuel. The blue bars are for diesel fuel, 59% Canola and 75% Canola respectively	144
Figure 4-15 Image of two different fuel sprays at $t_1=5$ ms. The top image shows a diesel fuel spray and the bottom image shows a 75% canola oil fuel spray. Avg. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μm , $t_3=12$ ms. Light sheet illumination.	145
Figure 4-16 Viewable region of the spray used in the PIV experiment (shown by the red rectangle). Diesel fuel, $D_{noz}=0.24$ mm, avg. $P_i=109$ MPa, $P_a=30$ bar, and $t_1=5$ ms. Light sheet illumination.	147
Figure 4-17 Image of a 75% canola oil spray with intensity count normalised to a range from 0 to 880. Avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs . Light sheet illumination.....	149
Figure 4-18 Instantaneous velocity profile plot with 32 x 32 pixel window, 50% overlap and one vector for each 32 pixels. PIV calculated from image in Figure 4-17. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	150
Figure 4-19 Combined vector plot with original image. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	151
Figure 4-20 Instantaneous vorticity plot about the y-axis. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	152
Figure 4-21 Instantaneous vorticity plot combined with the original image. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	153
Figure 4-22 Mean velocity profile (contours and vectors) with reduced vectors (25% on z-axis, 50% on x-axis) based on 211 samples. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	154
Figure 4-23 RMS of the velocity in m/s combined with overlayed mean velocity vectors. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	155

Figure 4-24 Reynolds stress of the mean velocity combined with overlaid mean velocity vectors. 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	156
Figure 4-25 The locations where dropsize measurements were made using shadowgraphy. The radial locations were set starting from the centre of the spray then 8 mm offset and 16 mm offset from centre of the spray. The locations set in the x-direction began at 81.3 mm, then 101.3 mm and 121.3 mm. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	158
Figure 4-26 Two sample images showing the large variations in dropsize that occurred between samples. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, location=(8,112.3).	163
Figure 4-27 Volumetric dropsize distribution of the eight locations from experiment 1. The smoothed curve was plotted using a moving average of the data points. Magnification 7.7x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	164
Figure 4-28 Volumetric CDF of dropsize from the eight locations from experiment 1. Magnification 7.7x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms. ...	165
Figure 4-29 Volumetric dropsize distribution results of the three different chamber pressures from experiment 2. The smoothed curve was plotted using a moving average of the data points. Magnification 27x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms.	167
Figure 4-30 Volumetric CDF of dropsize from the three different chamber pressures from experiment 2. Magnification 27x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms.	168
Figure 4-31 Volumetric dropsize distribution results comparing two different fuel viscosities from experiment 2. The smoothed curve was plotted using a moving average of the data points. Magnification 27x, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	169
Figure 4-32 Volumetric CDF of dropsize comparing two different fuel viscosities from experiment 2. Magnification 27x, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	170
Figure 5-1 Illustration of the KH instability breakup process.....	186
Figure 5-2 Illustration of KIVA-3 parcel allocation during KH droplet breakup. The child droplets are separated into a different parcel when the total mass of the child droplets is sufficiently large.....	186
Figure 5-3 Illustration of the implemented Star-CD v3.26 parcel allocation during KH droplet breakup. All droplets are grouped as one parcel with an average droplet diameter.	187

Figure 5-4 Meshed volume of the HPSC used for numerical simulation of the diesel spray. Maximum width = 174 mm, maximum height = 200 mm, chamber volume 4.63×10^6 mm ³	189
Figure 5-5 Cross-section view of HPSC meshed volume. The fine inner and outer mesh = green, coarse mesh = red, window cavity mesh = blue.	190
Figure 5-6 Magnified cross-section of the HPSC meshed volume. The three regions shown are the inner fine mesh region, outer fine mesh region and the coarse mesh region. The coarse window cavity mesh is not shown.	191
Figure 5-7 Penetration rate of the four different diesel spray simulations compared with the experimental results. In all cases, the Reitz-Diwakar breakup and MIOC collision models were used, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	197
Figure 5-8 Droplet SMD and RMS values for diesel spray comparing different atomisation models (simplified simulation and full simulation) with the experimental results. Results taken at coordinate $(8,112.3)\pm 5$. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	198
Figure 5-9 Droplet SMD and RMS values comparing the simulation and experimental results when the fuel viscosity was changed. Results taken at coordinate $(8,112.3)\pm 5$. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	200
Figure 5-10 Penetration rates of two different types of breakup model and the effect of fuel viscosity compared with the experimental results. In all cases, the Blob atomisation and MIOC collision models were used, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	202
Figure 5-11 Droplet SMD and RMS values of diesel and 75% canola oil spray comparing different breakup models with the experimental results. Results taken at coordinate $(8,112.3)\pm 5$. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	203
Figure 5-12 Penetration rate of two different simulations, with and without the MIOC model, compared with the experimental results. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	206
Figure 5-13 Droplet SMD and RMS values of the diesel spray comparing the effect of the MIOC model on the spray simulation and experimental results. Results taken at coordinate $(8,112.3)\pm 5$. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	207
Figure 5-14 CDF of the diesel spray simulations compared with the experimental results. The eight different simulation set-ups are detailed in Table 5-10. Results taken at coordinate $(8,112.3)\pm 5$. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=5$ ms.	209

Figure 5-15 Volumetric PDF of the diesel spray simulations compared with the experimental result. The eight different simulation set-ups are detailed in Table 5-10. Results taken at coordinate $(8,112.3)\pm 5$. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms.	210
Figure 5-16 CDF of the 75% canola oil spray simulations compared with the experimental results. The three different simulation set-ups are detailed in Table 5-11. Results taken at coordinate $(8,112.3)\pm 5$. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms.	211
Figure 5-17 Volumetric PDF of the 75% canola oil spray simulations compared with the experimental results. The three different simulation set-ups are detailed in Table 5-11. Results taken at coordinate $(8,112.3)\pm 5$. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms.	212
Figure 5-18 Magnified volumetric PDF of the 75% canola oil spray simulations compared with the experimental results. Only the KH-RT model simulations results are displayed to show a detailed comparison with the experiment. Results taken at coordinate $(8,112.3)\pm 5$. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms.	213
Figure 5-19 Log-log plot of the penetration rate with respect to time of the three different diesel fuel spray simulations compared with the three experimental results. The plot compares the effects of chamber pressure on the spray. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_i=5$ ms, $T=25$ °C.	217
Figure 5-20 Log-log plot of the penetration rate with respect to time of two different spray simulations compared with the two experimental results. The plot compares the effects of viscosity on the jet spray. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms, $T=25$ °C.....	217
Figure 5-21 Half cone angle plot with respect to time for the three different diesel fuel spray simulations compared with three experimental results. The plot compares the effects of chamber pressure on the jet spray. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_i=5$ ms, $T=25$ °C.....	218
Figure 5-22 Half cone angle plot with respect to time for two different fuel sprays. The plot compares the effects of viscosity on the spray. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_i=5$ ms, $T=25$ °C.	219
Figure 5-23 Normalised surface area plot of the simulated spray compared with the scattered light plot of the experimental spray at $P_a=20$ bar. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_i=5$ ms. Light sheet illumination.	221
Figure 5-24 Normalised surface area plot of the simulated spray compared with the scattered light plot of the experimental spray at $P_a=30$ bar. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_i=5$ ms. Light sheet illumination.	222

Figure 5-25 Normalised surface area plot of the simulated spray compared with the scattered light plot of the experimental spray at $P_a=40$ bar. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms. Light sheet illumination.....	223
Figure 5-26 Normalised surface area plot of the simulated spray compared with the scattered light plot of the experiment spray at $P_a=30$ bar. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms. Light sheet illumination.	224
Figure 5-27 Diesel spray volumetric CDF plot at different chamber pressures comparing the experimental results and simulation results. Results taken at coordinate $(8,112.3)\pm 5$. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms.....	226
Figure 5-28 Diesel and 75% canola oil spray volumetric CDF plot comparing the experimental results and simulation results. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	227
Figure 5-29 Experiment image of a 75% canola oil spray with intensity count normalised to a range from 0 to 880. Light sheet illumination, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	228
Figure 5-30 Simulation result plot showing the total droplet surface area (D^2) of a 75% canola oil spray. The D^2 plot replicates the scattered light image from the experiment. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	230
Figure 5-31 Experiment instantaneous velocity profile plot with a 32×32 pixel window, 50% overlap and half sets of vector arrows. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	231
Figure 5-32 Simulation instantaneous velocity profile plot with equivalent 32×32 pixel window, 50% overlapping and half sets of vector arrows. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	232
Figure 5-33 Experiment (top) and simulation (bottom) instantaneous vorticity about the y-axis. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	233
Figure 5-34 Four instantaneous cross-section plots from four simulation runs with different atomisation seeding values. The plot shows the total local surface area from the experiment's equivalent 16×16 pixel area with a 50% overlap. 20% normalisation, cross-section at 45° , cross-section thickness=2.5 mm, 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.....	235
Figure 5-35 Experiment (top) and simulation (bottom) mean velocity profile (contours and vectors) based on 211 samples. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	236

Figure 5-36 Mean velocity difference profile between the experiment and the simulation results. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	237
Figure 5-37 Experiment (top) and simulation (bottom) RMS of the velocity (contours profile) combined with the overlayed mean velocity vectors. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	238
Figure 5-38 Experiment (top) and simulation (bottom) Reynolds stress of the velocity (contours profile) combined with the overlayed mean velocity vectors. 75% canola oil, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms, $t_{12}=15$ μs	239
Figure 6-1 Log-log plot of the average and peak Weber numbers with respect to the z-axis. The plot shows three diesel sprays at different chamber pressures. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	242
Figure 6-2 Log-log plot of the average and peak Webers number with respect to the z-axis. The plot shows two sprays of different fuels (diesel fuel and 75% canola oil). $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=10$ ms.	243
Figure 6-3 Log-log plot of the average and peak Reynolds numbers with respect to the z-axis. The plot shows three diesel fuel sprays at different chamber pressures. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	244
Figure 6-4 Log-log plot of the average and peak Reynolds numbers with respect to the z-axis. The plot shows two sprays of different fuels. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=10$ ms.	245
Figure 6-5 Log-log plot of the average and peak Ohnesorge numbers with respect to the z-axis. The plot shows three diesel sprays at different chamber pressures. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	246
Figure 6-6 Log-log plot of the average and peak Ohnesorge numbers with respect to the z-axis. The plot shows two sprays of different fuels. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=10$ ms.	247
Figure 6-7 Average SMD with respect to the z-axis. The plot shows three diesel fuel sprays at different chamber pressures and the canola oil spray at $P_a=30$ bar. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	248
Figure 6-8 Close-up plot of the average SMD with respect to the z-axis. The plot shows three diesel sprays at different chamber pressures and the canola oil spray at $P_a=30$ bar. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	249
Figure 6-9 Cross-section FV plot of the $P_a=20$ bar diesel fuel spray. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=20$ bar, $t_1=0.5$ ms.	251

Figure 6-10 Two isosurface FV plots at different view angles. View at 45° x-axis, 30° z-axis and orthogonal projection (top) and equivalent cross-section view (bottom). Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=20$ bar, $t_i=0.5$ ms.	252
Figure 6-11 Cross-section FV plot of the $P_a=20$ bar diesel spray. Top plot FV value range from 0 to 0.0422. Bottom plot FV value range from 0 to 0.01. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=20$ bar, $t_i=5$ ms.	253
Figure 6-12 Two isosurface FV plot at different view angles. View at 45° x-axis, 30° z-axis and orthogonal projection (top) and equivalent cross-section view (bottom). Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=20$ bar, $t_i=5$ ms.	254
Figure 6-13 Cross-section FV plot of the $P_a=20$ bar diesel spray. Maximum FV value normalised at FV=0.01. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=20$ bar, $t_i=10$ ms. ...	255
Figure 6-14 Two isosurface FV plots at different view angles. View at 45° x-axis, 30° z-axis and orthogonal projection (top) and equivalent cross-section view (bottom). Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=20$ bar, $t_i=10$ ms.	256
Figure 6-15 Five isosurface plots of the $P_a=20$ bar diesel spray from $t_i=1$ ms to $t_i=5$ ms. $P_i=109$ MPa, $D_{noz}=240$ μ m.	258
Figure 6-16 Five isosurface plots of the $P_a=20$ bar diesel spray from $t_i=6$ ms to $t_i=10$ ms. $P_i=109$ MPa, $D_{noz}=240$ μ m.	259
Figure 6-17 Three FV isosurface plots of the diesel spray at different chamber pressures. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_i=10$ ms.	260
Figure 6-18 Isosurface plots of two different fuel sprays. $P_i=109$ MPa, $P_a=30$ bar, $D_{noz}=240$ μ m, $t_i=10$ ms.	261
Figure 6-19 Cross-section plot showing the droplet parcel diameter of a $P_a=20$ bar diesel fuel spray at $t_i=10$ ms. $P_i=109$ MPa, $D_{noz}=240$ μ m.	262
Figure 6-20 Filtered cross-section SMD plot (top) and FV isosurface plot (bottom) of a $P_a=20$ bar diesel spray at $t_i=10$ ms. Gaussian 3 x 3 filtered applied on the SMD plot, $P_i=109$ MPa, $D_{noz}=240$ μ m.	264
Figure 6-21 Two isosurface plots of the SMD at different view angles. View at 45° x-axis, 30° z-axis and orthogonal projection (top) and equivalent cross-section side view (bottom). Diesel spray, $P_i=109$ MPa, $P_a=20$ bar, $D_{noz}=240$ μ m, $t_i=10$ ms.	265
Figure 6-22 Three SMD isosurface plots of the diesel spray at different chamber pressures. $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_i=10$ ms.	266
Figure 6-23 Two SMD isosurface plots of two different fuel sprays. Diesel spray (top) and 75% canola oil spray (bottom). $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_i=10$ ms.	267

Figure 6-24 Three velocity cross-section plots of the $P_a=20$ bar diesel spray. Droplet velocity plot (top), gas velocity plot (middle) and relative velocity plot (bottom), $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	268
Figure 6-25 Cross-section z-component relative velocity (top), fractional volume (middle), and SMD (bottom) plots of the $P_a=20$ bar diesel spray showing the z-component only. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	270
Figure 6-26 Three velocity isosurface plots of the $P_a=20$ bar diesel spray. Droplet velocity plot (top), gas velocity plot (middle) and relative velocity plot (bottom), $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	272
Figure 6-27 Relative velocity isosurface plot of the $P_a=20$ bar diesel spray showing the z-component only. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=10$ ms.	273

List of Tables

Table 2-1 Droplet breakup regime at different Weber numbers with illustration. (Courtesy of Bayvel and Orzechowski [4] and Baumgarten et al. [22])	15
Table 2-2 Summary of various atomisation models' accuracy on the different in-nozzle physics features and the computational demand. (Courtesy of Baumgarten et al. [22] and Star-CD manual [47])	30
Table 2-3 Summary of various secondary breakup models and the accuracy of the representation of the real processes.	37
Table 3-1 Numerical simulation set-up specification for atomisation model evaluation.....	51
Table 3-2 Numerical simulation set-up specification of the AMC chamber for atomisation model evaluation.	52
Table 3-3 The experiment setup specifications for Park et al. [74].	63
Table 3-4 Set-up specifications for Star-CD simulation with settings that replicate Park et al. [74].	65
Table 3-5 Initial condition for dynamic drop drag simulation that replicated Park et al.'s experiment [23].	76
Table 3-6 Set-up specification in Star-CD for dynamic drop drag simulation.	76
Table 3-7 Droplet density calculation of three different meshes found in Figure 3-24	83
Table 3-8 Summary difference between the default O'Rourke and MIOC model.	85
Table 3-9 Turbulence model and sub-models used in the droplet collision simulation.....	88
Table 3-10 Set-up specification of the AMC chamber.	88
Table 3-11 List of case scenario settings for collision model evaluation.	90
Table 3-12 Turbulence model and sub-models used in the droplet collision simulation.....	108
Table 3-13 Different test case settings for the study of interpolation method and the relationship with collision model in diesel spray.	118
Table 3-14 Turbulence model and sub-models used in the droplet collision simulation.....	118
Table 4-1 List of penetration and cone angle experiment set-ups with different chamber pressures and fuel viscosities.	132
Table 4-2 Fuel physical properties (density and viscosity).....	133
Table 4-3 Specification of each PIV experimental set-up.....	148
Table 4-4 PIV general experiment specification.....	148
Table 4-5 Image sample size of different PIV experiment sets.	148

Table 4-6 Summary of the eight location coordinates where dropsize measurements were made in experiment 1. Avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	159
Table 4-7 Summary of the parametric set-up configurations of experiment 2. Avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $t_1=5$ ms, $t_{12}=1$ μs , location (0,112.3) and (8,112.3).	160
Table 4-8 Summary of the two dropsize experiment set-up specifications.....	161
Table 4-9 Dropsize results of experiment 1. Details of the set-up found in section 4.4.1. Magnification 7.7x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.....	162
Table 4-10 Dropsize results of experiment 2 at different chamber pressures. Magnification 27x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	166
Table 4-11 Dropsize results of experiment 2 comparing two fuels of different viscosity. Magnification 27x, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms	169
Table 4-12 Comparison of average PTV, micro PIV (μ -PIV) and macro PIV (M-PIV) results. Magnification=7.7x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms. ..	172
Table 4-13 Velocity difference in percentage comparing the PTV, micro PIV and macro PIV of diesel. Magnification=7.7x, diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	173
Table 4-14 Average PTV, micro PIV (μ -PIV) and macro PIV (M-PIV) comparison of 75% canola oil. Magnification 27x, 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.....	175
Table 4-15 Velocity difference in percentage comparing the PTV, micro PIV and macro PIV of 75% canola oil. Magnification 27x, 75% canola oil, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.	175
Table 5-1 Summary of the models used in the HPSC simulation.	192
Table 5-2 Summary of the full simulation conditions.....	193
Table 5-3 Summary of the physical properties of the diesel fuel and the 75% canola oil used in the simulation.	194
Table 5-4 Lagrangian atomisation models nominal evaluation cases.	196
Table 5-5 Summary of droplet SMD and RMS values for diesel spray comparing different atomisation models (simplified simulation and full simulation) with the experimental results. Results taken at coordinate (8,112.3) \pm 5. Diesel fuel, avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.....	199
Table 5-6 Summary of droplet SMD and RMS values comparing the simulation and experimental results when the fuel viscosity was changed. Results taken at coordinate (8,112.3) \pm 5. Avg. $P_i=109$ MPa, $D_{noz}=240$ μm , $P_a=30$ bar, $t_1=5$ ms.....	201

Table 5-7 Lagrangian secondary breakup models evaluation cases.....	201
Table 5-8 Summary of droplet SMD and RMS values of diesel fuel and 75% canola oil spray comparing different breakup models with the experimental results. Results taken at coordinate (8,112.3)±5. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_1=5$ ms.....	204
Table 5-9 Summary of droplet SMD and RMS values of diesel spray comparing the effect of the MIOC model on the spray simulation and experimental results. Results taken at coordinate (8,112.3)±5. Avg. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_1=5$ ms.	206
Table 5-10 Summary of the diesel fuel spray simulation cases for the study of dropsizes distribution.	208
Table 5-11 Summary of the 75% canola oil spray simulation cases for the study of volumetric dropsizes distribution.	211
Table 5-12 Summary of the model configurations used in the HPSC simulation for experimental validation.	215
Table 5-13 Summary of the four conditions used in validation of the simulation set-up.	215
Table 5-14 Diesel spray dropsizes summary at different chamber pressures showing mean, SMD, SMD % error, RMS and RMS/SMD of the experimental results and simulation results. Results taken at coordinate (8,112.3)±5. Diesel fuel, $P_i=109$ MPa, $D_{noz}=240$ μ m, $t_1=5$ ms.	225
Table 5-15 Diesel and 75% canola oil spray dropsizes summary showing mean, SMD, SMD % error, RMS and RMS/SMD of the experimental results and simulation results. Results taken at coordinate (8,112.3)±5. $P_i=109$ MPa, $D_{noz}=240$ μ m, $P_a=30$ bar, $t_1=5$ ms.	226

Nomenclature

Symbol	Description	Units
A_{noz}	Injection nozzle area	mm^2
b	Impact parameter used in the study of inter-droplet collision	
C_D	Drag coefficient (of the droplet)	
C_d	Discharge coefficient of the injector nozzle	
D	Current droplet diameter	μm
D_0	Initial droplet diameter	μm
D_{d1}	Droplet diameter of the first selected droplet	μm
D_{d2}	Droplet diameter of the second selected droplet	μm
D_{dif}	Diffraction limit of the microscope. $D_{dif} = 1.22 \cdot \Lambda \cdot f_{\#}$	μm
D_{P1}	Arbitrary diameter of the first selected parcel	μm
D_{P2}	Arbitrary diameter of the second selected parcel	μm
D_s	Stable droplet diameter	μm
D_{noz}	Nozzle diameter	mm
$E_{.95}$	Standard error at 95% confidence interval $E_{.95} = 1.96 \cdot \frac{s}{\sqrt{N}}$	
$e_{.95}$	Percentage of the standard error $e_{.95} = \frac{E_{.95}}{\bar{x}} \cdot 100\%$	%
E_n	Normalised error i.e. standard error divided by mean	
E_{xz}	u_x rate of change along z-axis direction $E_{xz} = du_x/dz$	s^{-1}
E_{zx}	u_z rate of change along x-axis direction $E_{zx} = du_z/dx$	s^{-1}

$f_{\#}$	Focus number (camera lens specific term). $f_{\#} = x/D$	
I_i	Turbulent intensity $I_i = \frac{s_i}{\bar{u}_i}$	
L_c	Liquid core length	mm
m	Mass of the droplet	kg
N	Droplet population in a given parcel or number of image sample	
P_i	Injection pressure	MPa
P_a	Ambient pressure	MPa
p	Probability	
R_{xz}	Reynolds stress about x-axis. $R_{xz} = \frac{\sum [(u_x - \bar{u}_x)(u_z - \bar{u}_z)]}{N}$	$m^2 s^{-2}$
r	Radius of the droplet	μm
s_N	Normalised RMS $s_N = \frac{s}{\bar{x}} \times 100\%$	
T	Temperature	$^{\circ}C$
t_0	Start of injection	
t_1	Time of first experiment recording measured from t_0	ms
t_2	Time of second experiment recording measured from t_0	ms
t_{12}	Time duration between the first and second recording	μs
t_3	Time at the end of injection measured from t_0	ms
u	Velocity (of the droplet or gas)	m/s
u_{rel}	Relative velocity between droplet and gas	m/s
V	Volume	m^3
x	Sample value or distance	
\bar{x}	Sample mean	

Δ	Ratio between two droplets (or difference of the two items)	
Λ	Wavelength of the light	nm
Λ_{KH}	KH instability wavelength	
Λ_{RT}	RT instability wavelength	
Ω_{KH}	KH instability growth rate	
Ω_{RT}	KH instability growth rate	
ϕ	Fractional volume of liquid in a given volume of gas	
μ	Dynamic viscosity	kg/(ms)
ρ	Density of the fluid	kg/m ³
σ	Surface tension (between liquid fuel and air)	N/m
τ_b	Breakup timescale	μ s
ω_y	Rate of rotation about y (out of plane vorticity). $\omega_y = E_{zx} - E_{xz}$	s ⁻¹

Subscript

0	Initial condition
1	First experimental recording of the current spray event
2	Second experimental recoding of the current spray event
3	End of injection
a	Gas (air) phase
inj	Parameter from injection of the spray
l	Liquid (Fuel) phase
rel	Relative value
s	Stable condition

Abbreviations

CAB	Cascade Atomisation Breakup model
CDF	Cumulative Distribution Function
CFD	Computational Fluid Dynamics
DOF	Depth of Field
ETAB	Enhanced Taylor Analogy Breakup model
FV	Fractional Volume (ϕ)
GS	Grid-Scale length (used in LES)
HFO	Heavy Fuel Oil
HPSC	High Pressure Spray Chamber
KH	Kelvin-Helmholtz (referring to the Kelvin-Helmholtz instability)
KH-RT	Kelvin-Helmholtz Rayleigh-Taylor Hybrid breakup model
LES	Large Eddy Simulation turbulence modelling technique
LIF	Laser Induced Fluorescence
MIOC	Mesh Independent O'Rourke Collision model
ND	Neutral Density (camera filter)
NS	Navier-Stokes equation
Oh	Ohnesorge number $Oh = \mu_l / \sqrt{\rho_l \cdot \sigma \cdot D}$
PDF	Probability Density Function
PDPA	Phase Doppler Particle Analyser
PIV	Particle Image Velocimetry
PTV	Particle Tracking Velocimetry
RANS	Reynolds-Average Navier-Stokes turbulence modelling technique
Re	Reynolds number $Re = \rho_a \cdot u_{rel} \cdot D / \mu$

RMS Root mean square or standard deviation of the sample (N)

$$RMS = \left(\frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2 \right)^{0.5}$$

RNG Renormalisation Group, a version of the k - ε turbulence model

RT Rayleigh-Taylor (referring to the Rayleigh-Taylor instability)

SGS Sub-Grid-Scale length (used in LES)

SMD Sauter Mean Diameter (D_{32})

TAB Taylor Analogy Breakup model

TDC Top Dead Centre

VCO Valve Covered Orifice (a type of injector nozzle design)

We Weber number $We = \rho_a \cdot D \cdot u_{rel}^2 / \sigma$